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DETERMINATION OF LOCAL MAGNITUDE, M_L, FROM STRONG-MOTION ACCELEROGRAMS

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ABSTRACT

A technique is presented for determination of local magnitude, M_L, from strong-motion accelerograms. The accelerograph records are used as an acceleration input to the equation of motion of the Wood-Anderson torsion seismograph to produce a synthetic seismogram which is then read in the standard manner. When applied to 14 records from the San Fernando earthquake, the resulting M_L is 6.35, with a standard deviation of 0.26. This is in good agreement with the previously reported value of 6.3. The technique is also applied to other earthquakes in the western United States for which strong-motion records are available. An average value of M_L = 7.2 is obtained for the 1952 Kern County earthquake; this number is significantly smaller than the commonly used value of 7.7, which is more nearly a surface-wave magnitude.

The method presented broadens the base from which M_L can be found and allows M_L to be determined in large earthquakes for which no standard assessment of local magnitude is possible. In addition, in instances where a large number of accelerograms are available, reliable values of M_L can be determined by averaging.

INTRODUCTION

The strong ground motion resulting from a major earthquake is the result of a very complex process, depending on the fault geometry, fault dimensions, and the rupture mechanism. The process is not understood in detail and in order to assess the effect of the ground motion upon structures of engineering interest, it is necessary to characterize the motion approximately by a simple set of variables. Usually, the characterization of strong shaking at a site is achieved by using relatively simple seismological parameters such as the magnitude of the earthquake and the distance from the causative fault. These parameters are then used to determine the amplitude and duration of the strong ground motion, using a variety of statistical methods (e.g., Housner, 1965; Donovan, 1974; Schnabel and Seed, 1973; Jennings *et al.* 1963). Among the several magnitude scales in current use, the local magnitude, M_L, introduced by Richter (1935) has the most direct relevance to engineering applications because M_L is determined within the period range of greatest engineering interest. The local magnitude is based on the amplitude recorded by the Wood-Anderson torsion seismograph with a natural period of 0.8 sec, a damping constant of $h = 0.8$, and a static magnification, $V = 2800$. Other magnitude scales such as the surface-wave magnitude, M_S, are not directly related to the strength of shaking in the frequency range of most interest in engineering, although they represent other important characteristics of the earthquake such as the fault dimension and the duration of the strong ground motion.

The characteristics of the different magnitude scales have not been applied consistently, however, and in the engineering and seismological literature the magnitude M is frequently used without denoting the kind of scale employed. For example, $M = 7.7$ is usually used for the 1952 Kern County earthquake. Gutenberg (1955) determined the magnitude of this earthquake by using both body waves and surface waves recorded at large distances ($\Delta \geqq 20°$). He obtained a value of 7.6 from long-period body waves and 7.6 to 7.7 from surface waves. The magnitude 7.7 is based on these determinations, but it does not necessarily represent the amplitude of the short-period waves at short distances that would determine M_L. Unfortunately, all the records of the Wood-Anderson seismographs operated by the California Institute of Technology went off-scale in the earthquake, precluding their use in determining M_L. Another example is the 1940 Imperial Valley earthquake which produced the well known El Centro accelerogram. This earthquake was originally given $M = 6.7$ by Gutenberg and Richter (1949a) but M was later revised to 7.1 (Richter, 1958). Although this second value is now routinely used in engineering applications, it is a surface-wave magnitude (Gutenberg and Richter, 1949b), and is not necessarily representative of the shorter period motions.

The significance of the local magnitude has motivated the present study which presents a technique for calculation of M_L from strong-motion accelerograms, with primary application to several southern California earthquakes.

Analysis

The Earthquake Engineering Research Laboratory of the California Institute of Technology has digitized and compiled nearly all of the significant strong-motion records from U.S. earthquakes from the first records obtained in 1933 through the San Fernando earthquake of 1971 (Hudson *et al.*, 1969 to 1976). Because the response of the strong-motion accelerograph is essentially equal to the ground acceleration over the displacement pass-band of the standard Wood-Anderson torsion seismograph, it is possible to synthesize a Wood-Anderson record from the accelerogram by using the strong-motion record as an acceleration input to an oscillator with the characteristics of the Wood-Anderson instrument. The results reported below were calculated this way by using a minor modification of a computer program developed to calculate response spectra (Nigam and Jennings, 1969).

The method employed is equivalent in this case to synthesizing the Wood-Anderson response by first deconvolving the accelerogram with the response of the accelerograph, and then convolving it with the response of the Wood-Anderson instrument.

Figure 1 shows examples of the accelerograms and the synthesized Wood-Anderson responses. Figure 2 compares the Wood-Anderson response of the 1971 San Fernando earthquake computed from the strong-motion record obtained at the Seismological Laboratory at the California Institute of Technology with a seismogram recorded at the same site by a 4X torsion seismograph whose response characteristics are similar to the standard Wood-Anderson instrument. The wave forms are nearly identical, although the amplitude of the synthesized record is about 35 per cent smaller than the observed record. This discrepancy may be due to two causes. First, the torsion seismograph is not calibrated very accurately (F. Lehner, personal communication, 1977), so that a 20 to 30 per cent error in the overall magnification is not unexpected. Second, the ground motion at the Seismological Laboratory was strongly polarized in the E-W direction as demonstrated by the strong-motion records (Hudson *et al.*, 1969 to 1976) and the seismoscope response (Borrill, 1971). Since the N-S component recorded the ground motion in the direction nearly perpendicular to the plane of polarization, a slight misalignment between the two instruments could have caused a considerable difference in the amplitudes. Despite this discrepancy in the amplitude, the overall agreement between the record is considered satisfactory.

Figure 3 shows an accelerogram from the Borrego mountain earthquake of 1968, the integrated ground velocity and displacement, along with the Wood-Anderson

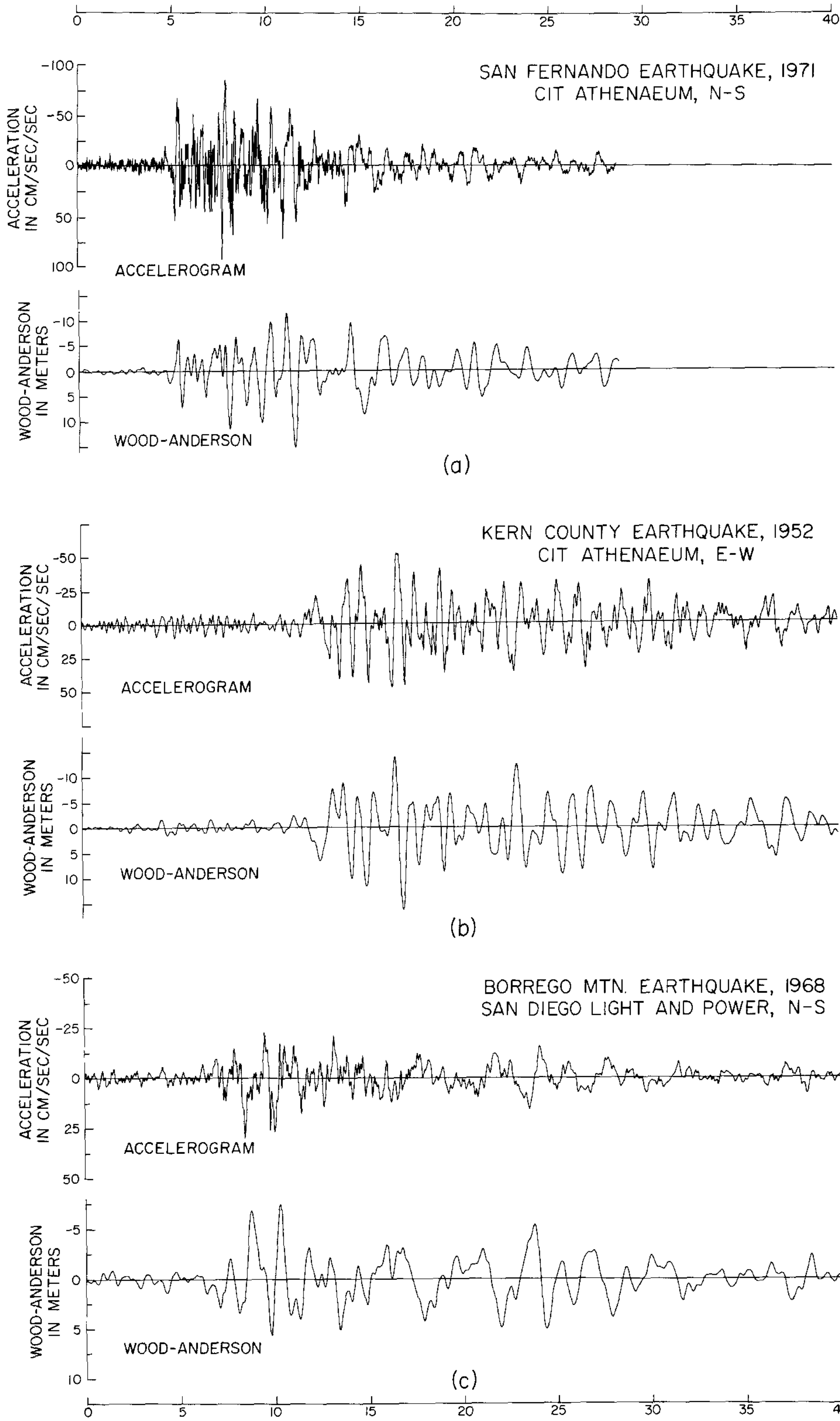

FIG. 1. Sample accelerograms and synthesized Wood-Anderson responses.

response. The characteristics of the Wood-Anderson instrument are not such that the response closely resembles the ground displacement, velocity or acceleration. It is seen from Figure 3, however, that the Wood-Anderson record is more like the ground velocity than either the displacement or acceleration.

RESULTS

The validity of the method is demonstrated by the results from the San Fernando earthquake shown in Table 1. There are a large number of accelerograms available for this earthquake; the ones included in Table 1 were selected to give a representative sample with respect to distance and azimuth. For the calculation of local

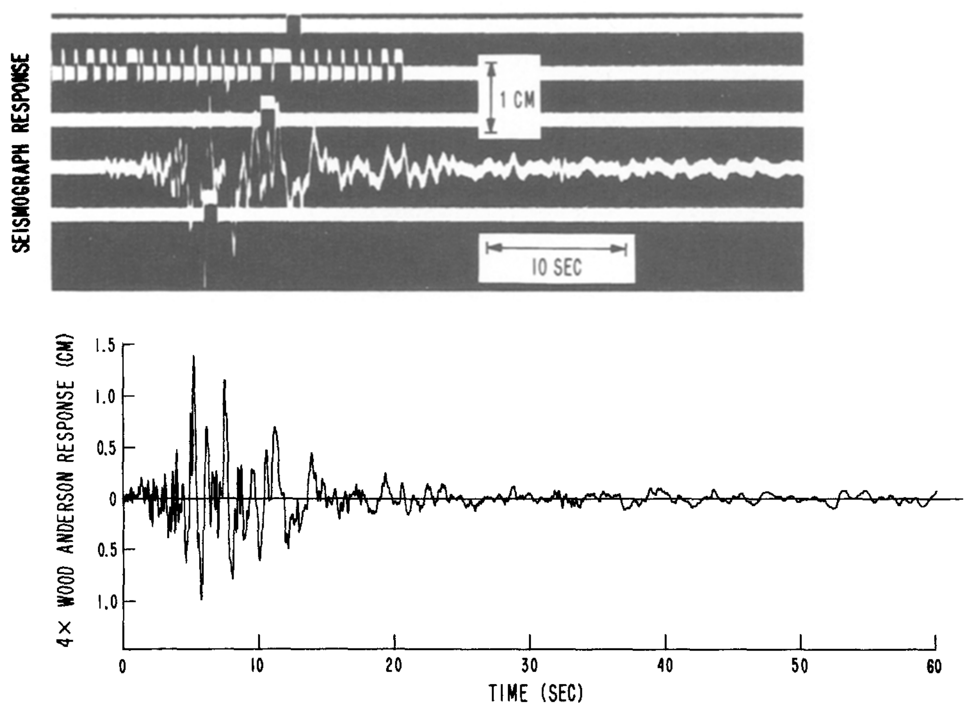

FIG. 2. Comparison of the record observed by a 4X torsion seismograph (*upper trace*) with the 4X Wood-Anderson response calculated from the strong-motion record. The records are the N-S component of the 1971 San Fernando earthquake obtained at the Seismological Laboratory at the California Institute of Technology.

magnitude the distances are measured with respect to Pacoima Dam. This point was inferred to be the approximate center of faulting, based on consideration of the surface faulting and the epicenters of the main shock and aftershocks (U.S. Department of Interior, 1971).

As noted in Table 1, an average value of $M_L = 6.35$, with a standard deviation of 0.26 is obtained by use of the strong-motion records. This value agrees very well with the average $M_L = 6.34$ determined from the Wood-Anderson records at four stations in southern California (see Appendix I).

Because of the characteristics of the Wood-Anderson seismograph, the maximum response does not necessarily occur at the same time as the maximum ground velocity or acceleration. For the 28 records from the San Fernando earthquake used in Table 1, the maximum response of the synthesized Wood-Anderson record occurred at about the same time as the maximum ground velocity in 70 per cent of the cases, and at the time of the maximum acceleration in 54 per cent of the data. All three functions peaked at about the same time in 40 per cent of the cases.

The results of M_L determinations for other major California earthquakes are summarized in Table 2. No station corrections were included in the computations of

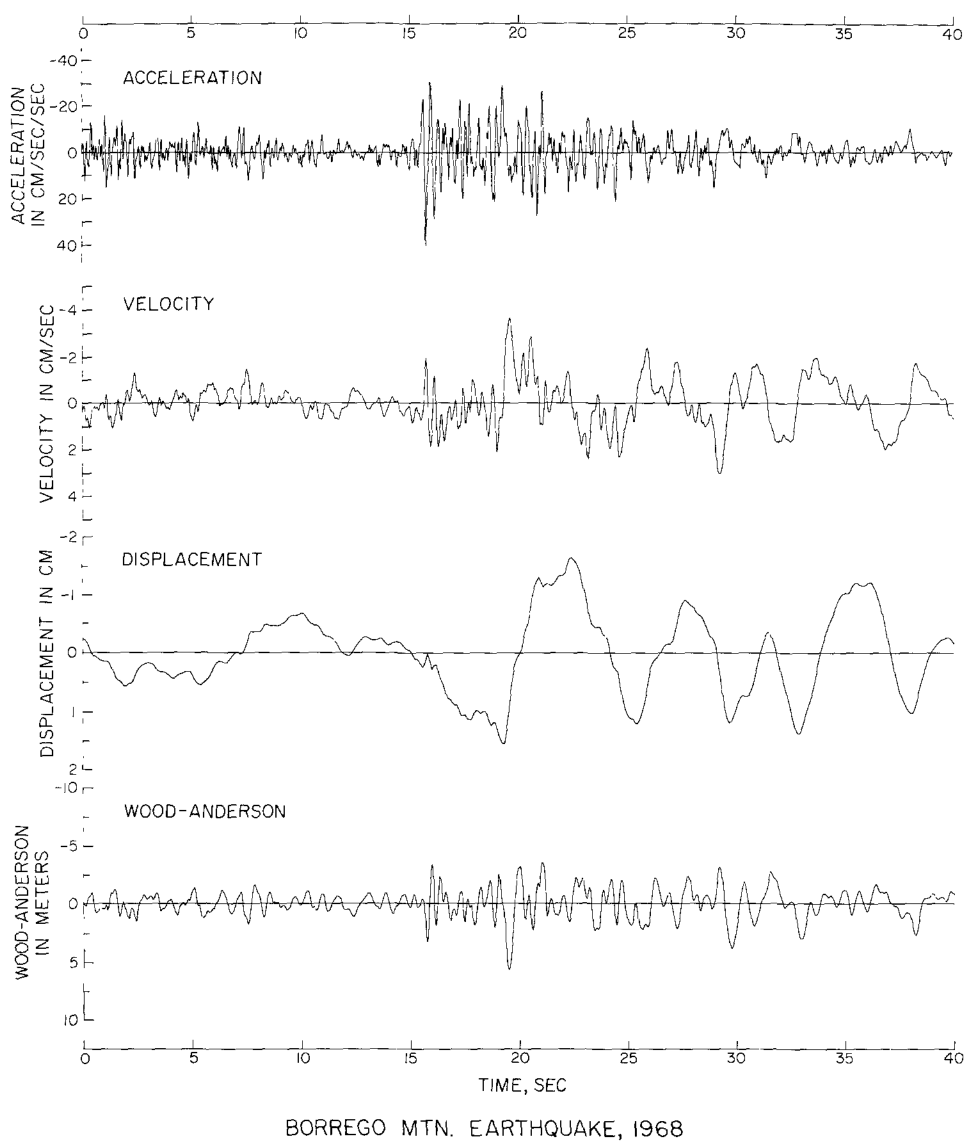

FIG. 3. Ground acceleration, velocity, displacement, and synthesized Wood-Anderson response for Borrego Mountain earthquake of 1968.

M_L, but station effects are thought to be minimized when the average is taken. In Table 2, distances are calculated from the origin taken either at the inferred center of faulting, denoted by F, or the epicenter, denoted by E, as indicated in the headings for each earthquake. In every case, horizontal distances, rather than hypocentral distances were used.

In the case of the 1966 Parkfield earthquake, the strong-motion array crosses the southernmost limits of the fault rupture (Cloud and Perez, 1967). Two sets of results are included for this earthquake: one in which the distance is measured from the nearest point on the fault, and another in which the distance used is that to the center of the zone of aftershocks. The average value of M_L obtained in the first case

TABLE 1

LOCAL MAGNITUDE M_L FOR THE 1971 SAN FERNANDO EARTHQUAKE DETERMINED FROM STRONG-MOTION ACCELEROGRAMS

No. 57,[a] San Fernando, February 9, 1971, F[b] 34° 20.04′; 118° 23.29′

Station	Ref.[c]	Component	Δ (km)	PP/2[d] (m)	T[e] (sec)	M_L
Pacoima	C041	S16E	~0	136	1.0	6.50
	C041	S74W	~0	89.5	0.5	6.30
Holiday Inn Orion	C048	N	14.5	50.2	0.6	6.30
	C048	E	14.5	31.2	1.0	6.10
Hollywood Storage Bldg.	D058	N	28.0	16.3	0.6	6.30
Parking Lot	D058	E	28.0	30.4	1.2	6.50
Santa Felicia Dam	E081	S08E	36.0	11.4	1.0	6.40
	E081	S82W	36.0	7.35	0.6	6.15
Pearblossom	F103	N	48.0	5.88	0.5	6.30
	F103	E	48.0	6.28	0.6	6.40
CIT Seismo. Lab.	G106	N	29.0	7.93	0.7	6.00
	G106	E	29.0	19.1	0.8	6.40
CIT Athenaeum	G107	N	33.0	13.3	0.8	6.40
	G107	E	33.0	18.9	0.8	6.50
CIT, JPL	G110	S82E	25.0	20.2	0.4	6.25
	G110	S08W	25.0	16.4	0.6	6.15
Palmdale	G114	S60E	37.0	21.5	1.4	6.60
	G114	S30W	37.0	13.8	1.4	6.45
15250 Ventura Blvd.	H115	N11E	21.0	26.3	1.8	6.15
	H115	N79W	21.0	25.3	1.8	6.10
Lake Hughes No. 1	J141	N21E	38.0	37.1	1.0	6.95
	J141	S69E	38.0	22.9	1.0	6.70
Lake Hughes No. 9	J143	N21E	34.0	6.74	0.3	6.10
	J143	N69W	34.0	6.40	0.5	6.10
3838 Lankershim Blvd.	L166	N	22.0	13.1	0.8	5.90
	L166	E	22.0	18.0	0.8	6.05
UCSB	O208	N42E	134	4.00	0.6	6.80
	O208	S48E	134	4.67	1.4	6.85
Average					0.88 ± 0.39	6.35 ± 0.26

[a] Earthquake No. refers to that in Index Volume of Strong-Motion Earthquake Accelerograms (Report No. EERL 76-02, California Institute of Technology, Earthquake Engineering Research Laboratory, 1976).

[b] F, coordinates of the center of the faulting; E, epicenter.

[c] Ref. denotes the reference number of the accelerogram in the EERL reports. The distance Δ is calculated from the coordinates of F or E given for the individual earthquake.

[d] PP/2 denotes $\frac{1}{2}$ of the maximum peak-to-peak amplitude (in meters) on the synthetic Wood-Anderson record ($T_0 = 0.8$, $h = 0.8$, $V = 2800$).

[e] T is the approximate period of the Wood-Anderson response at maximum amplitude.

is 5.91 and in the second case, 6.22. The first value is closer to the previously reported value of 5.6.

The local magnitudes were also calculated by this approach for approximately 30 other earthquakes, including many which have produced accelerograms important to engineering. These results are included in Table 3. Because only one or two accelerograms were available for most of the earthquakes in this table, and because

TABLE 2

LOCAL MAGNITUDE M_L FOR MAJOR CALIFORNIA EARTHQUAKES DETERMINED FROM STRONG-MOTION ACCELEROGRAMS

The magnitude listed for each earthquake is taken from the Caltech catalog (Hileman *et al.*, 1973) except No. 41, for which the catalog of U. C. Berkeley (Bolt and Miller, 1975) is used. For other explanations, see footnotes to Table 1.

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
No. 1, Long Beach Mar. 11, 1933 (1754 PST, Mar. 10) F 33°42′; 118°04′, M = 6.3	Long Beach Utilities Bldg.	V315	N	14.0	29.7	1.0	6.00
		V315	E	14.0	23.5	1.0	5.95
	Vernon CMD Terminal Bldg.	B021	S08W	36.0	25.0	0.8	6.70
		B021	N82W	36.0	23.8	1.0	6.60
	Los Angeles Subway Terminal	V314	N39E	42.4	14.6	1.6	6.60
		V314	N51W	42.4	21.7	1.4	6.75
Average						1.13 ± 0.30	6.43 ± 0.36
No. 14, Imperial Valley May 19, 1940 (2037 PST May 18) F 32°40′; 115°22.3′, M = 6.7	El Centro	A001	N	21.4	49.9	0.9	6.35
		A001	E	21.4	41.7	0.9	6.30
No. 24, Kern County July 21, 1952 F 35°10′; 118°45′, M = 7.7	Taft	A004	N21E	65.1	19.6	0.9	7.00
		A004	S69E	65.1	22.6	1.0	7.10
	Santa Barbara	A005	N42E	120	21.5	1.6	7.40
		A005	S48E	120	27.5	1.1	7.50
	Hollywood Storage Bldg. Parking Lot	A007	N	126	10.5	1.0	7.15
		A007	E	126	9.75	1.3	7.10
	CIT Athenaeum	A003	N	128	10.4	1.0	7.15
		A003	E	128	15.2	0.8	7.30
Average						1.09 ± 0.25	7.21 ± 0.17
No. 41, San Francisco Mar. 22, 1957 E 37°40′; 122°29′, M = 5.3	S. F. Golden Gate Park	A015	N10E	12.6	4.66	0.3	5.20
		A015	S80E	12.6	5.70	0.4	5.30
	S. F. State Bldg.	A016	S09E	15.8	5.59	0.5	5.35
		A016	S81W	15.8	6.66	0.6	5.40
	S. F. Alexander Bldg.	A014	N09W	17.4	3.06	0.8	5.10
		A014	N81E	17.4	2.59	0.4	5.05
	Oakland City Hall	A017	N26E	27.7	2.55	0.5	5.45
		A017	S64E	27.7	1.90	0.6	5.30
Average						0.51 ± 0.16	5.27 ± 0.14
No. 50, Parkfield June 28, 1966 (2026 PST June 27) F 35°53′; 120°27′, M = 5.6	Cholame Array No. 2	B033	N65E	22.8	92.2	1.0	6.75
		B033	N65E	0.08[a]	92.2	1.0	6.35

TABLE 2—*Continued*

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
	Cholame Array No. 5	B034	N05W	23.1	30.9	0.5	6.35
		B034	N05W	5.5[a]	30.9	0.5	5.95
		B034	N85E	23.1	27.7	0.5	6.25
		B034	N85E	5.5[a]	27.7	0.5	5.90
	Cholame Array No. 8	B035	N50E	24.7	15.0	0.9	6.05
		B035	N50E	9.7[a]	15.0	0.9	5.70
		B035	N40E	24.7	16.6	0.5	6.10
		B035	N40W	9.7[a]	16.6	0.5	5.70
	Cholame Array No. 12	B036	N50E	27.7	5.97	1.4	5.75
		B036	N50E	15.4[a]	5.97	1.4	5.35
		B036	N40W	27.7	8.56	1.4	5.90
		B036	N40W	15.4[a]	8.56	1.4	5.55
	Temblor	B037	N65W	34.5	16.5	0.3	6.40
		B037	N65W	10.7[a]	16.5	0.3	5.70
		B037	S25W	34.5	30.4	0.4	6.70
		B037	S25W	10.7[a]	30.4	0.4	6.00
	San Luis Obispo	B038	N36W	68.2	1.22	0.6	5.90
		B038	S54W	68.2	1.14	0.9	5.85
	Taft	U311	N21E	122	1.81	1.2	6.35
		U311	S69E	122	2.66	1.4	6.50
Average						0.85 ± 0.41	5.91 ± 0.33[b] 6.22 ± 0.32[c]
No. 55, Borrego Mountain Apr. 9, 1968 (1830 PST Apr. 8) F 33°08.5′N; 116°07.3′N, M = 6.4	El Centro	A019	N	65.2	29.8	1.4	7.15
		A019	E	65.2	14.2	1.6	6.90
	San Diego	A020	N	106	6.56	1.0	6.85
		A020	E	106	5.53	2.0	6.80
	San Onofre	B040	N33E	133	4.43	1.0	6.85
		B040	N57W	133	5.84	0.8	7.00
	Colton	Y370	N	150	2.49	0.8	6.60
		Y370	E	150	3.77	0.8	6.80
	Terminal Island	Y372	N21W	206	2.98	1.8	7.00
		Y372	S69W	206	2.10	1.6	6.90
	CIT Library	Y375	N	216	2.51	1.6	6.95
		Y375	E	216	2.61	1.6	6.95
	CIT Athenaeum	Y376	N	215	1.98	1.4	6.85
		Y376	E	215	2.43	1.4	6.95
	Hollywood Storage Bldg. Parking Lot	Y380	N	230	2.71	1.3	7.05
		Y380	E	230	3.61	1.8	7.20
Average						1.37 ±0.39	6.93 ± 0.14
No. 56, Lytle Creek Sept. 12, 1970 E 34°16.2′; 117°32.4′, M = 5.4	Wrightwood	W334	S65E	13.2	17.9	0.6	5.80
		W334	S25W	13.2	13.2	0.5	5.70
	Cedar Springs	W336	S54E	22.2	3.28	0.4	5.30
		W336	S36W	22.2	6.05	0.8	5.60
	San Bernardino Hall of Records	W338	N	29.8	5.98	0.8	5.85
		W338	E	29.8	3.74	0.8	5.65

TABLE 2—*Continued*

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
	Colton	W339	N	31.4	3.06	0.6	5.60
		W339	E	31.4	2.28	0.4	5.50
	CIT Library	W342	N	55.8	1.50	0.4	5.80
		W342	E	55.8	1.28	0.6	5.75
	JPL	W344	S82E	58.7	1.37	0.5	5.80
		W344	S08W	58.7	2.00	0.6	6.00
Average						0.58 ± 0.15	5.70 ± 0.18

[a] Distance to the nearest point on the fault.
[b] Average calculated with the shorter distances.
[c] Average calculated with the distances to the center of the aftershock zone.

there is, in some cases, uncertainty regarding the distance between the source and the accelerograph station, these values should be interpreted with caution. Other factors to be considered in interpreting Table 3 are the effect of the oceanic path and the depth of the source. In particular, 5 of the 13 events in Table 3 occurred in the Cape Mendocino area where the structure is complex and poorly known. The amplitude attenuation function ($-\log A_0$ on page 342 of Richter, 1958) used for the calculation of local magnitude was originally obtained by using earthquakes in southern California for which the source depth is shallow and the propagation path is continental. Thus, the application of the same amplitude attenuation function to earthquakes with a large focal depth or with partially oceanic paths may not be valid.

Discussion

The direct importance of the present analysis is twofold: (1) The local magnitude, M_L, can be determined for a very large earthquake such as the 1952 Kern County event, for which no standard measurement of M_L is possible. (2) Since a large number of accelerograms are available for many recent earthquakes (e.g., 1957, San Francisco; 1966, Parkfield; 1968, Borrego Mountain; 1970, Lytle Creek; and 1971, San Fernando), reliable values of M_L can be obtained by averaging.

One of the most important findings of this study is that the local magnitude, M_L, for the 1952 Kern County earthquake is 7.2 compared with the previously used value of 7.7. Because of the importance of this result, Professor Bruce A. Bolt was asked if he would examine the records obtained from the Wood-Anderson instruments of the Berkeley network during the Kern County earthquake. His result, $M_L = 7.2 \pm 0.2$, is in agreement with the value of 7.2 determined from the strong-motion records (Bolt, 1978). Although this value, 7.2, is the largest so far reported for M_L, the local magnitude tends to saturate as the surface-wave magnitude M_S increases, with the result that M_S substantially exceeds M_L for the larger earthquakes. This saturation has been interpreted in terms of the maximum effective tectonic stress (Brune, 1970).

Table 4 compares the values of different magnitude scales for some major California earthquakes. In this table $\bar{M}_L$ is the average of M_L (W-A) (M_L obtained from Wood-Anderson records), and M_L (S-M) (M_L obtained from strong-motion records). The average, $\bar{M}_L$, is weighted according to the number of stations used for the respective determinations.

The results from the southern California earthquakes, particularly the San Fernando event, indicate that the amplitude attenuation curve, $-\log A_0$, (Richter, 1958, p. 342) used by Richter to formulate M_L, which was necessarily obtained in the

TABLE 3

LOCAL MAGNITUDE CALCULATIONS, INCLUDING EARTHQUAKES WITH ACCELEROGRAMS IMPORTANT TO ENGINEERING

The magnitudes shown in Table 3 are from the Caltech catalog (Hileman *et al.*, 1973), denoted by PAS; from the U. C. Berkeley catalog (Bolt and Miller, 1975), denoted by BER; from Earthquake History of the United States, Part I (Epply, 1965), denoted by U.S.; and from Algermissen and Harding (1965), denoted by AH. For other explanations, see footnotes to Table 1.

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
No. 4, Lower California Dec. 30, 1934 E 32°15′; 115°30′, M = 6.5(PAS)	El Centro	B024	N	61.0	26.4	1.0	7.10
		B024	E	61.0	18.6	0.6	7.00
No. 5, Helena, Montana Oct. 31, 1935 (1138 MST) F 46°37′; 118°58′, M = 6.0(US)	Helena	B025	N	5.0	8.18	0.6	5.30
		B025	E	5.0	23.8	1.0	5.70
No. 6, Helena, Montana Oct. 31, 1935 (1218 MST) F 46°37′; 118°58′	Helena	U295	N	5.0	0.403	0.6	4.05
		U295	E	5.0	0.305	0.8	3.90
No. 7, Helena, Montana Nov. 22, 1935 (2058 MST, Nov. 21) F 46°37′; 118°58′	Helena	U296	N	5.0	0.193	0.3	3.70
		U296	E	5.0	0.315	0.3	3.95
No. 8, Helena, Montana Nov. 28, 1935 (0742 MST) F 46°37′; 118°58′	Helena	U297	N	5.0	3.77	0.7	5.00
		U297	E	5.0	3.63	0.5	5.00
No. 9, Humboldt Bay Feb. 7, 1937 40°30′; 125°15′, M = 5.8(BER)	Ferndale City Hall	U298	N45W	84.8	5.66	0.8	6.70
		U298	S45W	84.8	4.13	0.6	6.50
No. 11, Imperial Valley June 6, 1938 (1844 PST, June 5) 32°54′; 115°13′, M = 5.0(PAS)	El Centro	T275	N	33.1	1.00	0.4	5.20
		T275	E	33.1	1.15	0.5	5.30
No. 16, Santa Barbara July 1, 1941 (2351 PST, June 30) E 34°22′; 119°35′, M = 5.9(PAS)	Santa Barbara Court House	U299	N45E	12.2	25.2	0.6	5.95
		U299	S45E	12.2	29.3	0.6	6.00
No. 18, Los Angeles Nov. 14, 1941 E 33°47′; 118°15′, M = 5.4(PAS)	Long Beach	V316	N	5.6	9.34	1.2	5.45
		V316	E	5.6	13.4	1.3	5.60
	L. A. Chamber of Commerce Bldg.	V317	S50E	28.4	2.19	0.6	5.40
		V317	S40W	28.4	2.06	1.0	5.40
No. 19, Borrego Valley Oct. 21, 1942 E 32°58′; 116°00′, M = 6.5(PAS)	El Centro	T286	N	46.2	6.01	1.0	6.35
		T286	E	46.2	6.36	0.8	6.35
No. 20, Hollister Mar. 9, 1949 E 37°01′; 121°29′, M = 5.2(BER)	Hollister Public Library	U301	N89W	19.9	16.1	0.5	5.85
		U301	S01W	19.9	12.3	0.6	5.70
No. 21, Seattle Apr. 13, 1949 E 47°15′; 122°30′, M = 7.1(AH)	Olympia	B029	N04W	26.0	24.0	0.6	6.35
		B029	N86E	26.0	26.2	0.5	6.40
	Seattle	B028	S02W	48.0	15.9	1.0	6.70
		B028	N88W	48.0	12.3	0.8	6.60
No. 22, Imperial Valley Jan. 24, 1951 (2317 PST June 23) E 32°59′; 115°44′, M = 5.6(PAS)	El Centro	T287	N	27.1	4.79	0.5	5.65
		T287	E	27.1	4.79	0.5	5.60

TABLE 3—*Continued*

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
No. 27, San Luis Obispo Nov. 22, 1952 (1147 PST, Nov. 21) E 35°44′; 121°12′, M = 6.0(BER)	San Luis Obispo	V319	N36W	76.0	6.00	0.8	6.65
		V319	S54W	76.0	5.46	0.8	6.60
No. 29, Wheeler Ridge Jan. 12, 1954 E 35°00′; 119°01′, M = 5.9(PAS)	Taft	B031	N21E	43.0	7.49	0.6	6.35
		B031	S69E	43.0	5.79	0.6	6.15
No. 30, Hollister Apr. 25, 1954 E 36°56′; 121°41′, M = 5.3(BER)	Hollister	U305	N89W	26.8	7.11	0.6	5.80
		U305	S01W	26.8	8.47	0.6	5.90
No. 31, Lower California Nov. 12, 1954 E 31°30′; 116°00′, M = 6.3(PAS)	El Centro	T289	N	150	6.24	1.0	7.05
		T289	E	150	4.52	0.9	6.90
No. 32 Eureka Dec. 21, 1954 E 40°47′; 123°52′, M = 6.5(BER)	Eureka	A008	N11W	23.7	34.4	1.1	6.40
		A008	N79E	23.7	33.3	0.7	6.40
	Ferndale	A009	N44E	38.9	50.8	1.4	7.10
		A009	N46W	38.9	46.1	1.2	7.00
No. 33, San Jose Sept. 5, 1955 (1801 PST, Sept. 4) E 37°22′; 121°47′, M = 5.5(BER)	San Jose	A010	N31W	9.6	10.4	0.7	5.50
		A010	N59E	9.6	3.37	0.4	5.00
No. 36, Imperial County Dec. 17, 1955 (2207 PST, Dec. 16) E 33°00′; 115°30′, M = 5.4(PAS)	El Centro	T292	N	23.2	7.11	0.6	5.70
		T292	E	23.2	4.76	1.0	5.50
No. 37, El Alamo Feb. 9, 1956 (0633 PST) E 31°45′; 115°55′, M = 6.8(PAS)	El Centro	A011	N	125	7.20	1.0	7.00
		A011	E	125	9.96	1.2	7.10
No. 38, El Alamo Feb. 9, 1956 (0725 PST) E 31°45′; 115°55′, M = 6.1(PAS)	El Centro	A012	N	125	2.62	1.0	6.55
		A012	E	125	3.47	1.2	6.70
No. 39, Port Hueneme Mar. 18, 1957 E 34°07.1′; 119°13.1′, M = 4.7(PAS)	Port Hueneme	V329	N	4.0	20.8	0.6	5.70
		V329	E	4.0	11.2	1.0	5.50
No. 44, Hollister Jan. 20, 1960 (1926 PST, Jan. 19) E 36°47′; 121°26′, M = 5.0(BER)	Hollister Public Library	U307	N89W	8.0	7.94	0.7	5.40
		U307	S01W	8.0	4.61	0.6	5.15
No. 45, Ferndale June 6, 1960 (1718 PST June 5) E 40°49′; 124°53′, M = 5.7(BER)	Ferndale City Hall	U308	N46W	60.2	5.29	0.5	6.45
		U308	S44W	60.2	4.95	0.6	6.40
No. 46, Hollister Apr. 9, 1961 (2323 PST, Apr. 8) E 36°41′; 121°18′, M = 5.6(BER)	Hollister City Hall	A018	S01W	19.8	12.0	1.2	5.75
		A018	N89W	19.8	20.8	0.6	6.00
No. 46a, Hollister aftershock Apr. 9, 1961 (2325 PST, Apr. 8) E 36°41′; 121°18′, M = 5.5(BER)	Hollister City Hall	U309	S01W	20.6	10.4	0.8	5.70
		U309	N89W	20.6	14.6	1.0	5.90
No. 47, Eureka Sept. 4, 1962 E 41°00′; 124°24′, M = 4.9(BER)	Eureka Federal Building	V330	N79E	30.6	5.45	0.4	5.85
		V330	S11E	30.6	4.15	0.4	5.75

TABLE 3—*Continued*

	Station	Ref.	Component	Δ (km)	PP/2 (m)	T (sec)	M_L
No. 48, Puget Sound Apr. 29, 1965 E 47°24′; 122°18′, M = 6.5(AH)	Seattle Federal Office	U310	S32E	22.4	7.14	0.6	5.65
		U310	S58W	22.4	13.9	0.7	6.00
	Olympia Test Lab.	B032	S04E	61.0	14.2	0.8	6.90
		B032	S86W	61.0	17.5	1.0	7.00
No. 51, Gulf of California Aug. 7, 1966 E 31°48′; 114°30′, M = 6.3(PAS)	El Centro	T293	N	148	2.41	1.4	6.60
		T293	E	148	3.45	1.6	6.80
No. 52, N. California Sept. 12, 1966 E 39°25′; 120°09′, M = 6.0(BER)	Sacramento Telephone Bldg.	V332	N	149	1.99	1.0	6.50
		V332	E	149	2.09	0.7	6.50
No. 53, Eureka Dec. 10, 1967 E 40°29.5′; 124°41.6′, M = 5.6(BER)	Ferndale City Hall	U312	N46W	38.8	16.6	0.8	6.50
		U312	S44W	38.8	14.1	0.7	6.45
	Eureka Federal Bldg.	B039	S11E	57.0	3.30	0.6	6.20
		B039	N79E	57.0	3.84	0.8	6.20
No. 54, N. California Dec. 18, 1967 E 37°00.6′; 121°47.3′, M = 5.3(BER)	Hollister Public Library	U313	N89W	17.8	2.09	0.7	4.95
		U313	S01W	17.8	3.16	0.9	5.15
No. 49, Castaic July 16, 1965 (2346, July 15) E 34°29.1′; 118°31.3′, M = 4.0(PAS)	Castaic	V331	N	14.7	2.13	0.4	4.90
		V331	E	14.7	0.827	0.3	4.50
Hegben Lake Aug. 18, 1959 F 44°45′; 111°12′, M = 7.1(US)	Bozeman		N	100	4.16	0.6	6.65
			E	100	4.45	1.2	6.70
	Butte		N	176	2.90	0.8	6.85
			E	176	4.17	0.6	7.00

near-field from earthquakes of very small magnitudes, also holds in the near-field for magnitudes up to about 6½. That is to say, there is little in the present results to suggest that the attenuation relations used to establish M_L should be modified when applied to the strong ground motions associated with the near-field of moderate earthquakes.

A possible exception might occur in the case of earthquakes like the 1966 Parkfield and the 1957 Port Hueneme events. The near-field ground motions in these cases resemble simple displacement pulses (the accelerograms are essentially three pulses). In the case of the Parkfield earthquake, the values of M_L diminish with distance in the near-field, decreasing from a value of 6.35 near the fault to about 5.5 at 15 km. The ground motion also changes from its simpler, pulse-like character to a more complex, dispersed wave form over the same distance (Cloud and Perez, 1967; Housner and Trifunac, 1967). These observations suggest that a different attenuation rate of Wood-Anderson response may be associated with this type of accelerogram, and that using the standard distance-amplitude relations may result in higher readings for M_L at close-in stations.

It is seen from Table 4 that the average M_L for the Kern County earthquake, 7.2, is significantly larger than that for the San Fernando earthquake. It should not necessarily be inferred from this that the maximum amplitude of the Wood-Anderson response for the Kern County earthquake in the near-field is larger than that for the San Fernando earthquake by a factor corresponding to the difference in the magnitudes. The larger earthquakes are probably more complex and the larger values of M_L determined at large distances for the 1952 Kern County earthquake may represent the constructive interference of motions from a number of sources, rather than the effect of one large, coherent source.

In the case of the Borrego Mountain earthquake, however, the motion recorded at El Centro at 65 km indicates that much of the energy may have been released in a single large pulse. Burdick and Mellman (1976) and Heaton and Helmberger (1977) studied this earthquake by using teleseismic body waves and the El Centro strong-motion record, respectively. They concluded that the Borrego Mountain earthquake is represented by a relatively simple event. In this case, the maximum amplitude of the Wood-Anderson response in the near-field may have been very large.

Because of their intrinsic differences, M_S and M_L tend to be influenced by different features of the earthquake source. In general, it is expected that earthquakes with larger M_S will have larger fault dimensions, longer durations of shaking, and multiple sources of energy release, whereas those with larger M_L will be associated with stronger ground motions near 1-sec period. By using both M_L and M_S, it should be

TABLE 4

COMPARISON OF M_L OBTAINED FROM WOOD-ANDERSON RECORDS (SEE APPENDIX I), M_L OBTAINED FROM STRONG-MOTION RECORDS (THIS STUDY), SURFACE-WAVE MAGNITUDE, AND THE U.S.C.G.S. SHORT-PERIOD BODY-WAVE MAGNITUDE m_b

		M_L (W-A)	M_L (S-M)	$\bar{M}_L$	M_S	m_b (1 sec)
Long Beach	1933	6.3	6.4	6.4	6.2[a]	—
Imperial	1940	6.5	6.3	6.5	7.1[a]	—
Kern County	1952	—	7.2	7.2	7.7[a]	—
San Francisco	1957	5.3	5.3	5.3	—	—
Parkfield	1966	5.6	5.9	5.8	6.0[b]	5.3
Borrego Mt.	1968	6.7	6.9	6.8	6.7[b]	6.1
San Fernando	1971	6.3	6.3	6.3	6.6[b]	6.2

[a] Gutenberg and Richter (1949b).
[b] Determined from WWSSN long-period records.

possible to provide an improved characterization of the strong ground motion from major earthquakes.

An examination of the results in Table 3 shows a tendency for the values of M_L determined for earthquakes in northern California to exceed the value of M_L determined from seismological instruments. From a group of 13 earthquakes in northern California, 7 showed M_L from the accelerograms exceeding previously reported magnitudes by 0.5 or more, while only one case occurred in which M_L from the accelerograms was 0.5 or more below previously given values. However, there are not enough records from any one earthquake to be positive about this trend. In the case of the 1957 San Francisco earthquake (Table 2), in which several records are available, the results are consistent with the previously reported magnitude of 5.3. Hence, the significance of the tendency seen in Table 3 is not clear.

In the case of the Puget Sound earthquakes of 1949 and 1965, the values of M_L reported for the smaller 1965 event are generally consistent with the previously reported value of 6.5, but the value of M_L for the larger 1949 event shown in Table 3 is about one-half magnitude below the commonly used value of 7.1. In this case it is believed that the difference is due primarily to the value of 7.1 being a surface-wave magnitude [according to the worksheets of Gutenberg and Richter (1949b), this value is obtained from surface waves after the depth correction is applied], although the applicability of the local magnitude scale to the relatively deep earthquakes in the Puget Sound region is itself somewhat questionable.

In addition to expanding the instrumental base from which the local magnitude, M_L, can be determined, this method of finding local magnitude is expected to be useful in the determination of engineering design criteria. For major projects, the earthquakes controlling the design are normally of specified magnitudes, and are associated with rupture along specified portions of the causative faults. Under these conditions, if accelerograms can be selected which are representative of the design earthquake in terms of duration and frequency content, the accelerograms can be scaled to produce synthetic Wood-Anderson responses that are consistent at the given distance with the local magnitude of the design earthquake. Thus, the use of statistical relations between local magnitude and amplitude of ground motion could be supplanted in some instances by a simple deterministic relation. In addition to this direct application, design ground motions determined by other methods can be examined by calculating the synthetic Wood-Anderson response, determining the local magnitude, and comparing the value with that of the design earthquake.

As noted above, the calculation of the synthetic Wood-Anderson response is the same as used to calculate the response spectrum of the accelerogram. Because of the importance of M_L and the convenience of the calculation, it is recommended that one-half the peak-to-peak amplitude of the Wood-Anderson response be included in the calculations routinely made in the processing of strong-motion accelerograms.

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Appendix I

Local magnitude determined from the Wood-Anderson records (data from the original event cards filed at the Seismological Laboratory, California Institute of Technology).

Imperial Valley—1940

PAS 6.3	;	TIN 6.5	;	HAI 6.6		Ave: 6.5

Parkfield—1966

PAS 5.7	;	BAR 5.2	;	RVR 5.8	;	
CWC 5.6	;	Berkeley 5.5				Ave: 5.6

Borrego Mountain—1968

PAS 6.7	;	CWC 6.55	;	RVR 6.65	;	
SBC 6.85						Ave: 6.7

San Fernando

RVR 6.15	;	SBC 6.4	;	CWC 6.3	;	
PAS 6.6						Ave: 6.4

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